

PB85-106706

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(U.S.) Environmental Sciences Research Lab.
Research Triangle Park, NC

Oct 84



U.S. Department of Commerce
National Technical Information Service

NTIS

EPA-600/D-84-247
October 1984

Fluid Modeling of Blocking and Upstream Influences
of Stable Flow over Two-Dimensional Hills

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U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA-600/D-84-247	2.	3. RECIPIENT'S ACCESSION NO. PB85 10670 6
4. TITLE AND SUBTITLE Fluid Modeling of Blocking and Upstream Influences of Stable Flow over Two-Dimensional Hills		5. REPORT DATE October 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Roger S. Thompson and William H. Snyder ¹		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Sciences Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO. CDTA1D/09 (Task 3004) FY-84
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE EPA/600/09
15. SUPPLEMENTARY NOTES 1. On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.		
16. ABSTRACT Evidence of upstream influences observed in towing-tank experiments of stable flow over two-dimensional hills is presented. The influences take the forms of blocked fluid and columnar disturbance modes. Two hill shapes were used and the start-up method and depth of linear stratification were varied.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 12
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

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INTRODUCTION

Fluid modeling is a useful technique for the study and analysis of the dispersion of pollution from sources located near complex terrain features. However, fluid modeling of stable flow over two-dimensional objects has been found to produce results that must be evaluated with much care.

A concept that has proved quite useful for the description of the flow over three-dimensional hills is that of the dividing streamline. Sheppard (1956) derived an integral expression balancing the kinetic energy of a fluid parcel with its change in potential energy if it were raised through a stable density gradient. Applying this formula to the flow approaching a hill, he determined the height of the streamline that has sufficient energy to clear the hilltop. Fluid below this streamline must pass around the hill while the fluid above it may pass over the hilltop. Sheppard's formula for the dividing-streamline height H_s , adapted for liquid in a tank is

$$\frac{1}{2} \rho U_{\infty}^2(H_s) = g \int_{H_s}^h (z-h) (\partial \rho / \partial z) dz$$

where ρ is the fluid density, $U_{\infty}(H_s)$ is the approach flow speed at a height H_s above the surface, g is the acceleration due to gravity, h is the height of the hill, and z is the height above the surface. This formula must be solved iteratively to determine H_s . For a uniform approach flow and a linear density stratification, however, it reduces to $H_s/h = 1 - F$, where F is the Froude number U_{∞}/Nh , with N being the Brunt-Vaisala frequency $(-(g/\rho)d\rho/dz)^{1/2}$.

The application of the dividing-streamline concept to describe the flow over three-dimensional hills has been quite successful (Snyder et al, 1984). A point source located on or very near the dividing streamline will result in a plume that impacts the hill surface, producing a ground-level concentration that is approximately equal to the concentration that would have been measured at the plume centerline at that point in the absence of the hill (Snyder and Hunt, 1984). Plumes from sources located above the dividing streamline pass over the hill while those from sources below the dividing streamline pass around the hill.

For flow approaching a two-dimensional hill in very stable stratification, direct application of Sheppard's integral formula will yield a height for the dividing streamline (or surface). However, there are no ends of the hill for the fluid below the dividing streamline to pass around. The fluid in this lower layer will be blocked upstream of the hill. This is an unsteady situation in that the distance this blocked fluid extends upstream must grow with time. In a finite-length towing tank, the end wall restricts this growth and, thus, modifies the upstream conditions (Foster and Saffman, 1970).

Horizontally propagating waves, referred to as "columnar disturbance modes" have been observed in stratified tanks (Wei et al, 1975). These modes have zero frequency but group velocity $C(n) = ND/n\pi$, where n is the number of the mode and D is the depth of the tank. All modes with group velocities greater than the tow speed of the model will propagate upstream of it. These waves are reflected from the end walls of the tank and return to influence the flow near the obstacle. Wong and Kao (1970) theoretically predicted the amplitudes of the columnar disturbance modes. Their results indicated that the amplitudes increase with increasing mode number.

Much of the previous work on stable flows over ridges has been directed toward lee-wave formation and structure. However, Long (1953, 1954, and 1955) performed both theoretical and experimental analyses of stable flows over "easy shapes" in a stratified tank. He, however, avoided strongly stable stratifications. Wei et al (1975) towed circular cylinders and a vertical flat plate in their linearly-stratified tank. They only made one tow at a Froude number (based on the cylinder radius) of less than 1.0; $F = 0.78$. For this tow, a layer of fluid extending at least 27 radii upstream was observed to approach the cylinder at a speed of 0.7 times the tow speed. Baines (1979) performed a series of tows with a surface mounted, two-dimensional model and the same model with different sizes of gaps at one end. He reported a blocked region of fluid for tows of the two-dimensional model at Froude numbers less than 0.5. His data suggested that the depth of the blocked layer was one-half the obstacle depth for $F < 0.5$, with no blocking for larger F . Weil et al (1981) data, however, suggested a continuous change of blocked layer depth with F , with no blocking for $F > 0.5$.

To examine the nature and effects of these columnar modes and upstream blocking, four tows were performed in the EPA Fluid Modeling Facility's Water Channel/Towing Tank. The model used for three of the tows was a vertical fence that spanned the width of the tank. The other tow used a Witch of Agnesi cross section. The first (base case) tow was made with the fence and a linear density gradient through the depth of the tank. The normal rapid start-up procedure was used for this tow wherein the speed of the towing carriage was preset and the power was turned on bringing the carriage to full speed in about 1/2 second. A second tow was made using the Witch of Agnesi model with all other parameters the same to evaluate the influence of the model shape.

Many tows are often performed on one filling of the tank. Each tow destroys the linearity of the density profile mainly in thin layers near the top and bottom of the tank. Additional tows are performed after first skimming water off the top of the tank while adding saturated salt water at the bottom. This results in a linear layer at the top (where the model is towed) with the original N and a layer of constant density at the bottom. In the third tow, then, the effects of the reduction in the depth of the linear layer was examined by towing the fence when the depth of the linear had been greatly reduced. The last tow used a slow start-up to investigate whether the start-up conditions influenced the nature of the upstream effects.

OBSERVATIONS AND RESULTS

The experiments described here were conducted in the EPA Fluid Modeling Facility's Water Channel/Towing Tank (Figure 1). The tank's test section is 1.2 m deep, 2.4 m wide, and 25 m long. Models are mounted on a platform (baseplate) and suspended from the towing carriage into the stratified fluid. For additional details of the facility, see Thompson and Snyder (1976) or Hunt et al (1978).

Two models were used: a vertical fence ($h = 18.8$ cm) that spanned the width of the test section and a two-dimensional hill with a Witch of Agnesi cross section ($z = ha^2/(x^2 + a^2)$ with $h = 18.8$ cm and $a = 14.9$ cm.). The stratification in the tank was typically the maximum linear gradient obtainable using salt water. The saturated salt water on the bottom of the tank had a specific gravity of 1.2; the fresh water at the top had a specific gravity of 1.0. Thus, a typical value of N was 1.33 rad/s.

The influence of the columnar modes can be observed by dropping potassium permanganate crystals into the tank to create a vertical line of dye upstream of the model. Figure 2 shows a photograph of the deformation pattern of the dye line upstream of the vertical fence caused by the columnar disturbance modes. The tow speed was such that 9 modes could propagate upstream. The position where the dye crystals were dropped into the tank was 18.6 h upstream of the fence just after the mode-7 disturbance reached that point. The photograph was taken just prior to the calculated time of arrival of the mode-8 disturbance. Hence, the first 7 modes should have acted to deform the dye line. Whereas there is some question as to what happens near the top and bottom surfaces, the presence of the sixth mode is clearly evident from the number of peaks in the deformed dye line.

Changes in the density upstream of the model as each tow progressed were determined by drawing a set of samples of the fluid from 25 levels (2 cm intervals). This was done at four times during each tow. The model moved about 1.5 m during the drawing of each set of samples. The mid-points of the model position for the sampling periods were about 0.63 m, 6.2 m, 12.0 m, and 18.0 m from the starting position. The samples were collected at 1.0 m from the upstream end of the test section. Each sample's density was determined by measuring the displaced weight of a plumb bob suspended in the sample. A density difference was determined for each sample by subtracting the density at the same height before the tow commenced. For comparison of runs, these density differences were divided by the difference in density between the hilltop and surface before the tow to obtain "normalized density differences".

Figure 3 contains data from four tows. A tow of the fence with the linear stratification extending through the depth of the fluid (108 cm) using the normal rapid start serves as a reference case. To examine the influence of the shape of the model, a tow was made using the Witch of Agnesi model. This "easy shape" (maximum slope = 39 degrees) produced essentially the same density differences as the vertical fence. Since many tows are made after skimming the top fluid and adding saturated salt water at the bottom of the tank, a tow was performed to determine if this affected the development of the density differences. A tow identical to the first tow with the fence except that instead of a full depth linear density gradient, the linear region extended only to a depth of only 73 cm (the bottom 35 cm was saturated salt water). No change in the density difference profiles was observed. An additional tow was made with the fence slowly brought up to speed to determine if the upstream pattern was influenced by the impulsive start-up procedure normally used. The model was brought to tow speed by manually adjusting the speed control from zero to tow speed over a period of 30 seconds. Again, no change was observed in the profiles of density difference. However, this slow start complicates the calculation of the positions of the columnar wave fronts as the tow progresses.

Similar tows were also made for axisymmetric, three-dimensional models for which deformation of dye lines were observed, but upstream density differences were negligible until the model approached very near the end of the tank where the maximum normalized density difference was about 10 percent of that for a two-dimensional hill.

CONCLUSIONS AND DISCUSSION

Columnar disturbance modes are generated upstream of two-dimensional obstacles in stratified flows. These modes modify the approach flow conditions in an unsteady manner. For very stable approach flows, blockage of fluid upstream of the model results in changing velocity and density profiles. The group velocities of the columnar modes are calculable. In a towing tank, these columnar modes are reflected from the end walls and return downstream to influence the flow field near the obstacle. The point at which the slowest travelling mode meets the fastest reflected mode can be estimated and used to determine a portion of a tow with a quasi-steady-state velocity profile. If this occurred far from the end of the tank before the density differences rapidly increased, observations could be made while the conditions were nearly steady. The approach flow would have to be described by the perturbed velocity profile and the modified density gradient as they existed at the upstream limit of this region. As a practical matter, however, extraordinarily long tanks are required in order to obtain sufficiently large periods of "steady-state" in which to make meaningful observations. By including viscous effects, the upstream extent of the blockage effects will be finite and can be estimated. Tritton (1977) presents an order-of-magnitude argument that for a typical towing tank situation ($F = 0.2$, $U_{\infty} = 5$ cm/s, and $h = 20$ cm) predicts the blocked region to be a wedge that extends upstream about 50 km.

The application of results from towing-tank studies of stable flow over two-dimensional obstacles must include interpretation of the columnar modes and blockage effects. The rapid start from rest in the towing tank does not have an analog in the atmosphere. How the flow evolved to a stable flow toward the ridge must be considered. Since all real ridges have ends, the influence of the end effects must also be examined.

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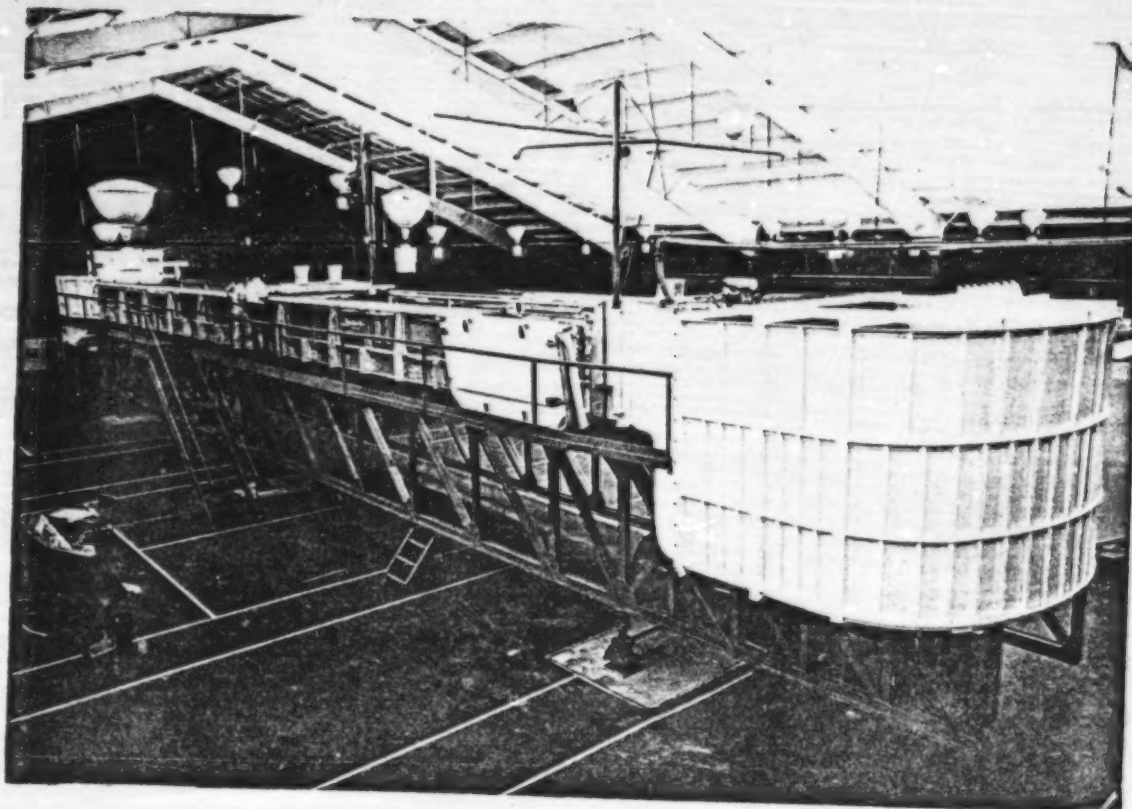


Figure 1. The Environmental Protection Agency, Fluid Modeling Facility's Water Channel/ Towing Tank.

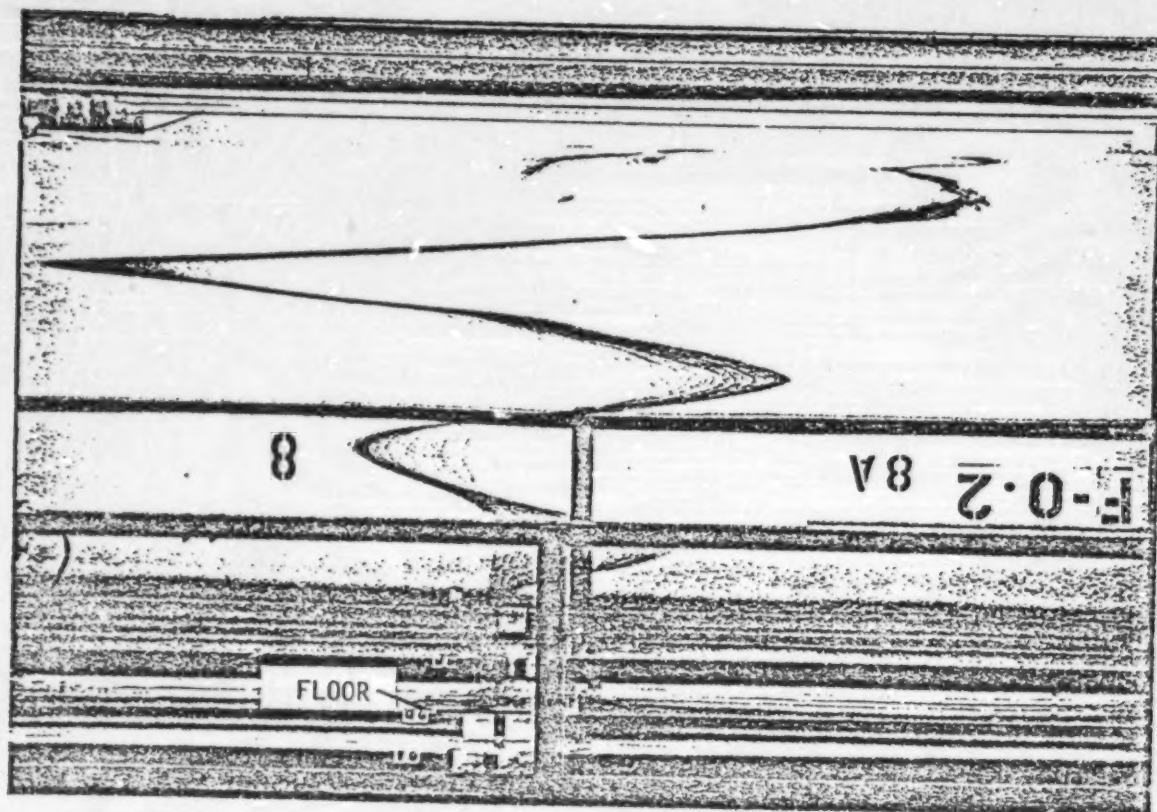


Figure 2. Deformation of vertical dye line by columnar disturbance modes 16m upstream of starting position of fence. Dye line was formed when fence was at $x=12.5\text{m}$ ($18.6h$) upstream of fence. Photograph was taken when fence was at $x=12.8\text{m}$ ($11.6h$ upstream of fence). Fence is out of photograph approaching from the left.

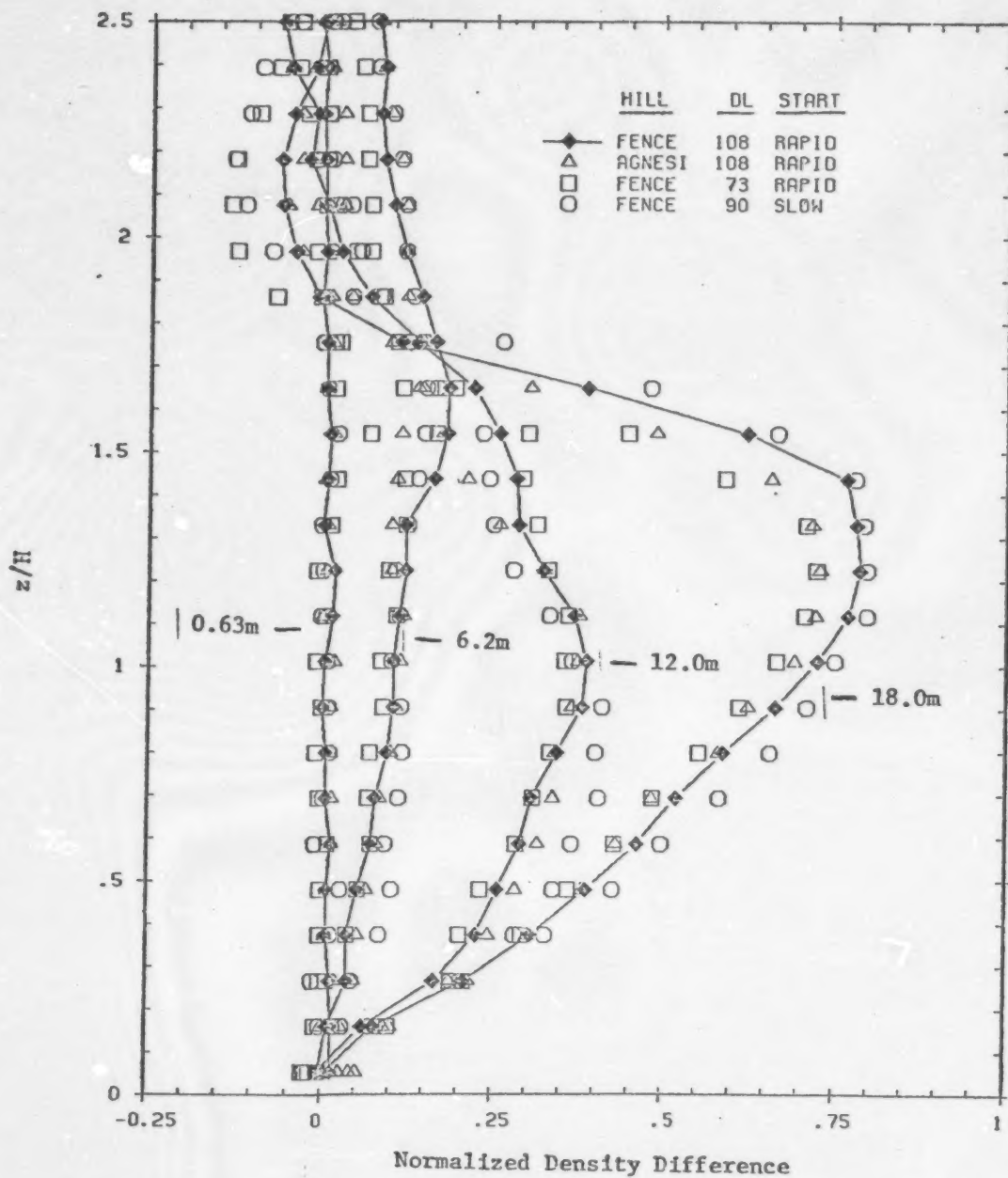


Figure 3. Vertical profile of normalized density differences obtained 21m upstream of model starting position. Four profiles are shown for each tow, when hill was centered at 0.63m, 6.2m, 12m, and 18m. The solid lines are drawn through the reference case, a fence with the depth of the linear stratification (DL) equal to the depth of the fluid in the tank (108cm) and a rapid start.